White Noise in silicon-based planar metal-semiconductor-metal photodiodes

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***Abstract*-Low-frequency 3-100 kHz shot noise (white noise) emerging from photoinduced current in Mo/n-Si/Mo structures leaving undepleted region has been observed under different bias and optical intensity conditions. The measurements revealed that the current noise observed depends not only on the illumination intensity levels but also on bias voltage. The current noise observed is expressed as $S(\omega)=2I\Gamma^2$ and analyzed, where I and Γ^2 is the average current and noise factor, respectively. The measurements reveal that Γ^2 has strong bias dependence, lying $\Gamma^2\sim 0.01$ to about unity corresponding to simple shot noise. Such experimental results are explained, stating that the reduction of cross correlation between drift and diffusion currents and autocorrelation of drift current component determining the level of noise occurs with decrease in SCR width bias-dependent. To explain the behavior of observed noise more properly, we propose, in addition to the mechanisms above, that the reduction in autocorrelation effect of each current component plays an important role to decrease the relevant noise to such extremely low levels.**

Keywords: Planar metal-semiconductor-metal; optical sensor; photocurrent control; shot noise

I. INTRODUCTION

The noise in an electronic device is categorized mainly into three. They are shot noise, 1/f noise or Flicker noise and thermal noise or Johnson noise [1-3]. When a two terminal semiconductor device is carrying an average (dc) current, the device inevitably exhibits so-called shot noise (white noise). At low frequencies where the noise is independent of the frequencies, the current noise spectral density associated with the average current I is usually formulated as given in ”(1)”.

$$S(\omega)=2qI\ (A^2/Hz) \tag{1}$$

which is called the full (or simple) shot noise. In case of practical devices, however, “(1)” is sometimes modified to fit the noise observed as

$$S(\omega)=2qI\Gamma^2\ (A^2/Hz) \tag{2}$$

where Γ^2 is the noise ratio or the noise factor representing the ratio of the noise to full shot noise [1-4]. In case that the noise is affected by the transit-time of carriers, the noise ratio would be the function of frequency [4]. Thus, the noise ratio would be regarded as a kind of the noise measure of the device under consideration. The relation $\Gamma^2=1$ has generally been accepted in existing theories for two-terminal semiconductor devices such as photodiodes and photoconductors [6-7].

II. EXPERIMENTAL

The samples were prepared as follows. We performed electron-beam evaporation of Mo 2000 Å thick at an initial vacuum of about 3×10^{-4} Pa onto an n-type silicon of resistivity of 10 Ω-cm. Mo film so formed works as Schottky-barrier metal to silicon and electrodes as well. The inset in Fig.1 shows the configuration of the electrodes, which was completed by photolithography lift-off technique. The size of both electrodes is the same and of $3\times3 mm^2$. The sample is of single slit type. The separation between the electrodes is 20 μm, which is wide enough for the two depletion regions of both junctions not to contact each other even when bias is applied. Under a bias, the anode is forward-biased and the cathode is reversed-biased. Thus, the band diagram of the structure under a bias much larger than its built-in voltage is assumed a single junction. From the forward current-voltage (I-V) characteristics and capacitance-voltage (C-V) characteristics under dark of independent Schottky-barriers, the barrier height and built-in voltage were estimated to lie around 0.70 eV and 0.23 eV, respectively [4].

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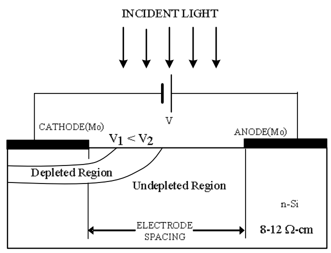

Figure 1. Schematic illustration of MSM structure having widely-separated electrodes under a bias.

III. MEASUREMENT PROCEDURE

The current versus applied bias (I-V) characteristics were measured under optical illumination and in the dark conditions. The block diagram of the set up for measurements of I-V characteristics is shown in Fig. 2. A neutral-density (ND) filter was used to control the device under test.

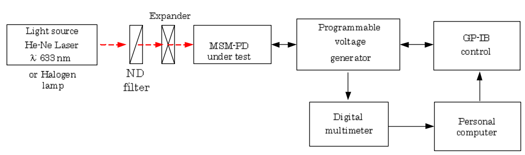

Figure.2. Block diagram of current-voltage I-V characteristic measurement system PC- controlled.

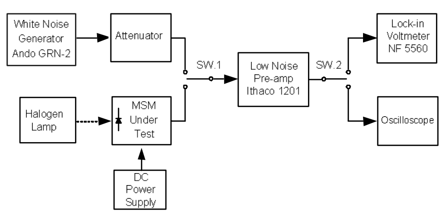

Figure 3. Block diagram of noise measurement system. For calibration of the system and noise observation in time domain, sw.1 and sw.2 are switched, respectively.

The noise measurements were performed using the system pictured in Fig.3. The frequency range of the noise measurements is from 3 kHz to 100 kHz. The noise to be detected was introduced into a 2 kΩ load resistor series-connected with the device under test, the voltage drop across the load was then introduced to a low-noise preamplifier (Ithaco 1201) and finally detected by a lock-in voltmeter (NF 5560). To check the system characteristic, a white noise generator (Ando GRN-2) was used. To irradiate the device, a xenon lamp dc-operated was used as a light source, the intensity of which was controlled by an ND filter.

IV. RESULT AND DISCUSSION

Figure 4 shows the typical photocurrent versus relations at room temperature under different illumination levels from a halogen lamp. Here the photocurrent component was obtained by subtracting the current under dark from the device current at each corresponding bias voltage. Here the photocurrent component was obtained by subtracting the current under dark from the device current at each corresponding bias voltage.

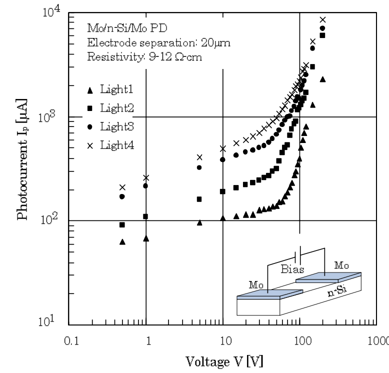

Figure 4. Photocurrent-voltage characteristics of a Mo/n-Si/Mo structure having 20μm electrode separation.

Each plot seems to be divided into two regions: the gradually increasing and rapidly increasing regions with bias. Since the present sample has the electrodes widely separated to avoid electronic interference between two junctions, the lateral separated in the depleted region would be more efficient to generate the photocurrent than the residual undepleted neutral region.

A. Photocurrent dependence

Figure 5 shows the typical noise-current relationship at 10 kHz for a 20 μm spaced electrode sample. From this measurement, one finds that the plot is straight, resulting in coincidence with the relationship predicted from "(1)" and "(2)". The dotted line shows the one for Γ^2=1 to guide the eye.

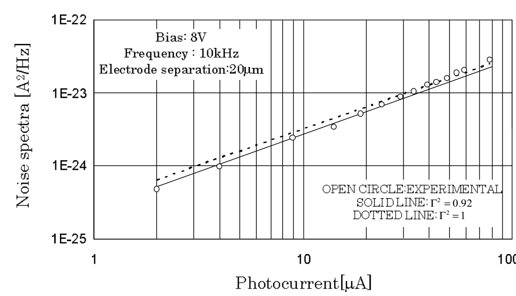

Figure 5. Experimental 10 kHz noise-photocurrent relationship of a planar Mo/n-Si/Mo system having 20 μm electrode separation

From the slope of this line, one can extract the corresponding noise factor for the case that the dark leakage current can be ignored comparing to the photoinduced current. The noise factor for this sample obtained in such a manner lies around Γ^2=0.92.

Many samples having various electrode separations ranging from 20μm to 2000μm were prepared. Figure 6 presents the result of noise factor for these samples where the spectra are frequency independent. Thus, it can be confirmed that the noise factor, Γ^2, is apparently smaller than unity that is expected from the simple shot noise theory [7-9]. Furthermore, there seems no dependence of the noise factor on the electrode separation although the values of noise factor are scattering. The broken line corresponding to Γ^2=0.89 shows the average value of all experimental points obtained.

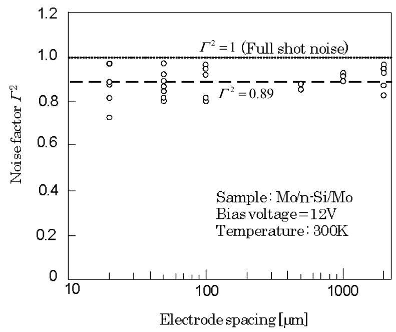

Figure 6. Experimental noise factor of Mo/n-Si/Mo structures, electrode spacing of which 20-2000 μm. Broken line shows the average noise factor for all samples examined (Γ^2=0.89). Dotted shows full shot noise level.

B. Bias dependence

Measurements for noise spectra at low frequencies were performed. The frequency range examined is from 10 kHz to 100 kHz, where the noise spectral density is independent of the frequency.

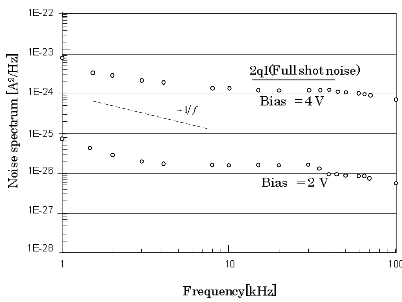

Figure 7. Noise spectra of a 20 μm separated electrode sample at two different bias of 2V and 4V at a current of 6-7 μA.

In lower frequency region than 10 kHz, flicker noise is dominant as shown in Fig. 7 for 20μm-separated electrode sample, where broken line shows the slope of flicker noise and solid line shows full shot noise respectively to guide the eye.

Figure 8 shows the noise-photocurrent relationship in log-log scale at 10 kHz for a sample, taking bias voltage as a parameter. Here, the noise and the photocurrent were obtained by subtracting the noise in the dark from the noise as measured and by subtracting the corresponding dark current at the same bias from the device current as measured, respectively. From these noise measurements, one finds that the plots are straight, resulting in coincidence with the relationship predicted from "(1)" and "(2)".

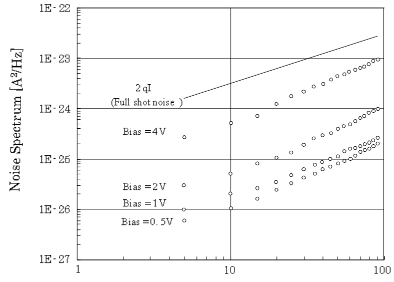

Figure 8. Shot noise spectra versus photocurrent of a Mo/n-Si/Mo structure at 10kHz, taking the bias voltage as a parameter.

When the bias voltage increases, the corresponding noise is also elevated, and asymptotically approach full shot noise given by the solid line calculated from "(1)". That is, the noise ratio defined in "(2)" is an increasing function of bias voltage, whilst the relation expressed by "(2)" is maintained within these plots. When the bias is at 0.5V, the corresponding noise ratio lies around two orders of magnitude lower than that of full shot noise. This extremely small noise ratio is not completely explained by the consideration of the planar metal-semiconductor-metal (MSM) structure, where spatially uniform carrier generation is taking place.

According to the existing theory of the autocorrelation function for semiconductor materials [1-4], the correlation function $c(s)$ represents the number of carriers present at the instant t that still contribute to the current fluctuation I at the instant (t+s). In a semiconductor, carriers may be taken out of circulation not only by arriving at the electrode on one-side, but also by recombination or trapping inside the material. Consequently,

$$c(s) = (1-s/\tau_2)\exp(-s/\tau_1) \quad \text{for } s<\tau_2 \qquad (3)$$

And

$$c(s) = 0 \quad \text{for } s>\tau_2 \qquad (4)$$

Here τ_1 is the average free time of the carriers between their generation by incident light and subsequent recombination; τ_2 is the average drift or diffusion time of the carriers. The autocorrelation function reduces to $c(s)=(1-s/\tau_2)$ if $\tau_2<<\tau_1$; all carriers then enter the active area at electrode on one side and leave the electrode on the other side of the area. Therefore, the full shot noise formula "(1)" should be expected; this case applies if the active area is very narrow.

If the electric field E is applied, a drift velocity is superimposed on the random motion of electrons; this give rise to shot effect within semiconducting material between the electrodes. This current fluctuation is due to the drift of the electron in the field and even after collision the electrons drift again in similar way until the electrons are captured by positive ions or recombination. This condition means that most electrons taking part in the conduction are liberated inside the semiconductor and are captured again before they arrive at the positive electrode. Under such condition, $\tau_1<<\tau_2$ and thus the autocorrelation function reduces to

$$c(s) = \exp(-s/\tau_1) \qquad (4)$$

Few carriers then enter the area at one side or leave it at other side; instead, most of them are created inside the area and captured again. In this case, the noise intensity is much less than the full shot noise intensity, $2qI$. Let us consider the case that the applied bias is relatively high such as 4V in Fig.8. It can presumably be assumed that the internal electric field becomes higher than under the lower biases as the numerical simulation predicts [3-5]. Under this condition, the autocorrelation function for the photogenerated carriers in the depleted region is relatively large, although the autocorrelation function coefficient for the carriers generated in the undepleted region is small. This could be the reason why the noise ratio lies at higher levels at a bias of 4V for the present structure. In order to explain such small noise ratio as observed, such a noise is attributed to the small relevant autocorrelation function of the currents at lower biases [5-8]. That is, making use of "(9)", very small autocorrelation function c(s) for the structure would be expected since the internal field in the depleted region is low enough to satisfy the relation $\tau_1 << \tau_2$.

Therefore, an extremely small autocorrelation function for the drift current can occur, while the autocorrelation coefficient for the diffusion current remains unchanged at low level.

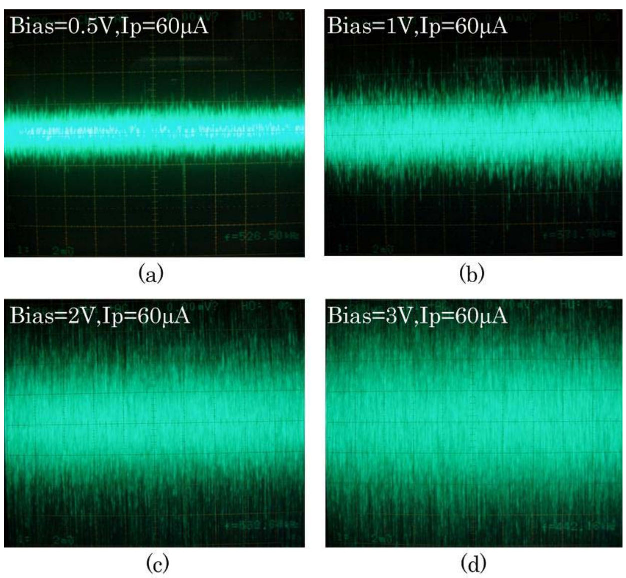

Figure 10. Oscilloscope traces of instantaneous noise under different biases at the same current of 60μA. Ver.:2mV/div., Hor.:200μsec/div.

The photographs in Fig. 10 (a)-(d) show the instantaneous noise on an oscilloscope at the same photocurrent but different biases for a sample under test. It is apparent that the noise varies rapidly with applying bias even under the same current level. As mentioned in a two-terminal semiconductor device carrying an average (dc) current, the associated noise would be of full shot noise type. The qualitative explanation for these experimental results giving rise to such low levels of noise is as follows. Accordingly, the change of depletion width cannot give rise to the reduction of autocorrelation of carriers than expected in Mo-Si systems.

V. CONCLUSION

The noise characteristics at low-frequency region ranging 10 kHz-100 kHz, where the noise is frequency-independent, were measured of planar Mo/n-Si/Mo optical sensor structures under optical illumination. The current noise spectral density observed was found to be not only current-dependent but also bias-dependent. The noise ratio for these structures was lower than simple shot noise by two orders of magnitude under some cases, depending on the bias applied. These low-noise behaviors have been qualitatively explained and attributed to three mechanisms: (1) No crosscorrelation between the drift current due to carriers emerging from the depleted region and the diffusion current due to carriers emerging within the diffusion length from the boundary with the depleted region. (2) Spatially uniform carrier generation in both depleted and undepleted regions. (3) Small autocorrelation coefficient of the drift- and diffusion-currents coming from low internal field in accordance with small applying bias.

It can be mentioned that such low photoinduced shot noise of these structures is of much interest from the view point of the signal-to-noise (S/N) ratio of optical sensing structures.

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